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Title:

METHOD AND MEANS FOR FEEDING ELECTRIC ENERGY TO A PORTABLE
POWER TOOL ;

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Inventor(s):   HARTWIG C SVERKER M (SE);   LJUNG ERIK A (SE) ;

Applicant(s):   ATLAS COPCO AB (SE) ;

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ABSTRACT:

A method and a means for feeding electric energy to a portable power tool is based on a
principle according to which the brushless AC motor of the tool is individually supplied with power
from a solid state inverter type power supply by which the amplitude and frequency of the AC
current are automatically and individually adapted to the instantaneous load conditions
experienced by the motor.

(54) **Method and means for feeding electrical energy to a portable power tool**

(57) The brushless AC motor (23) of the tool is individually supplied with power from a solid state inverter by which the amplitude and frequency of the AC current are automatically and individually adapted to the instantaneous speed of and load conditions experienced by the motor 23. The motor load is sensed by detecting the DC current to the inverter and the amplitude of the AC current supplied by the inverter is controlled by pulse width modulation.
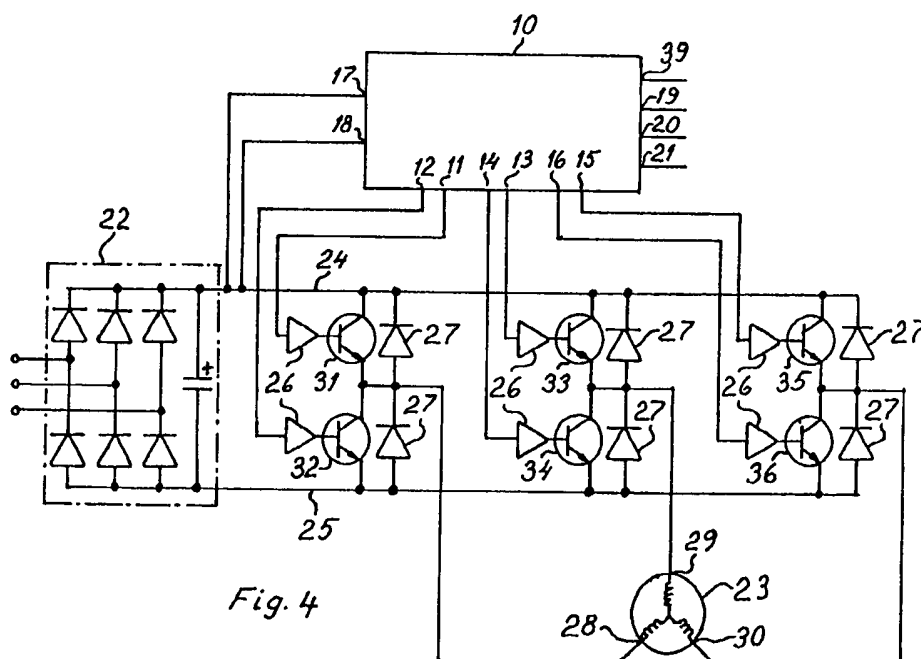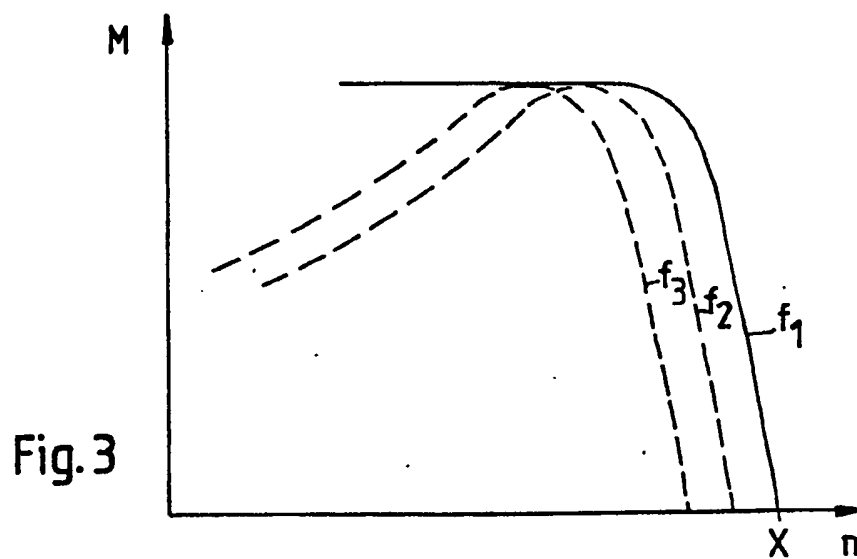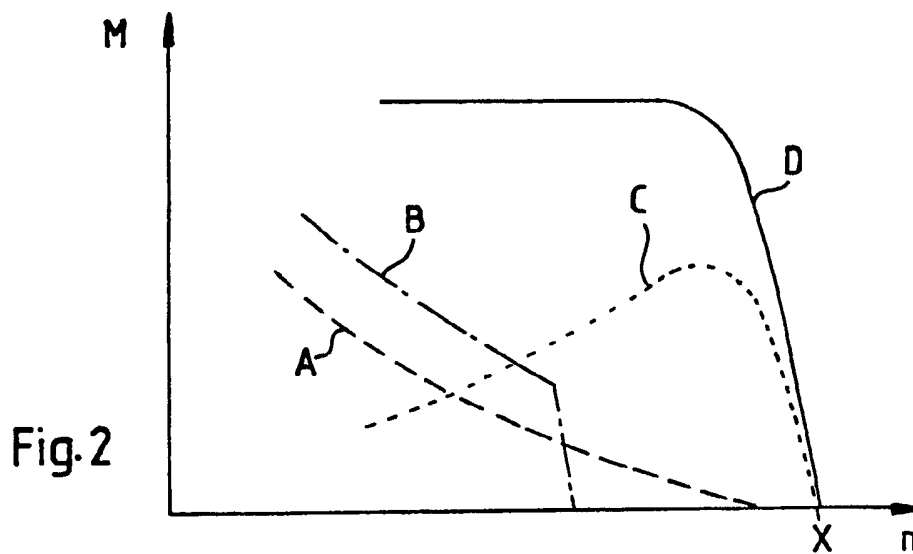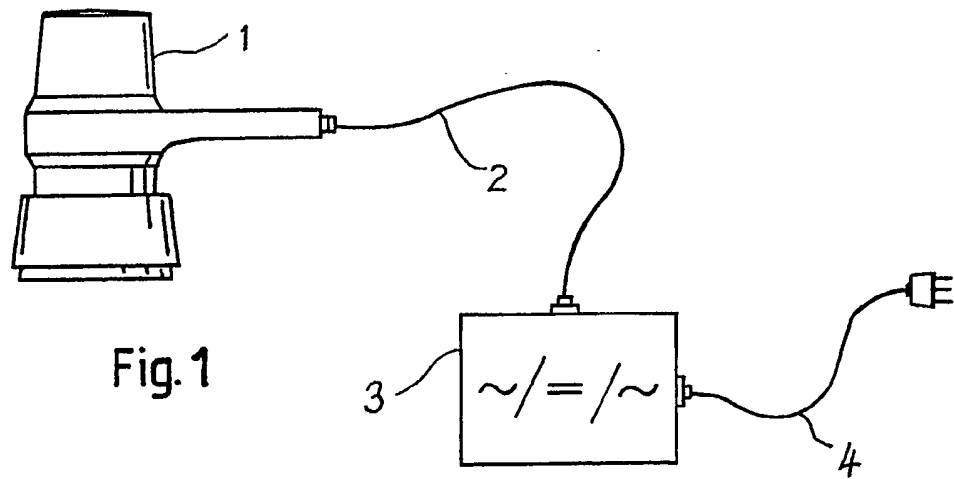
Fig. 4

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Fig.1

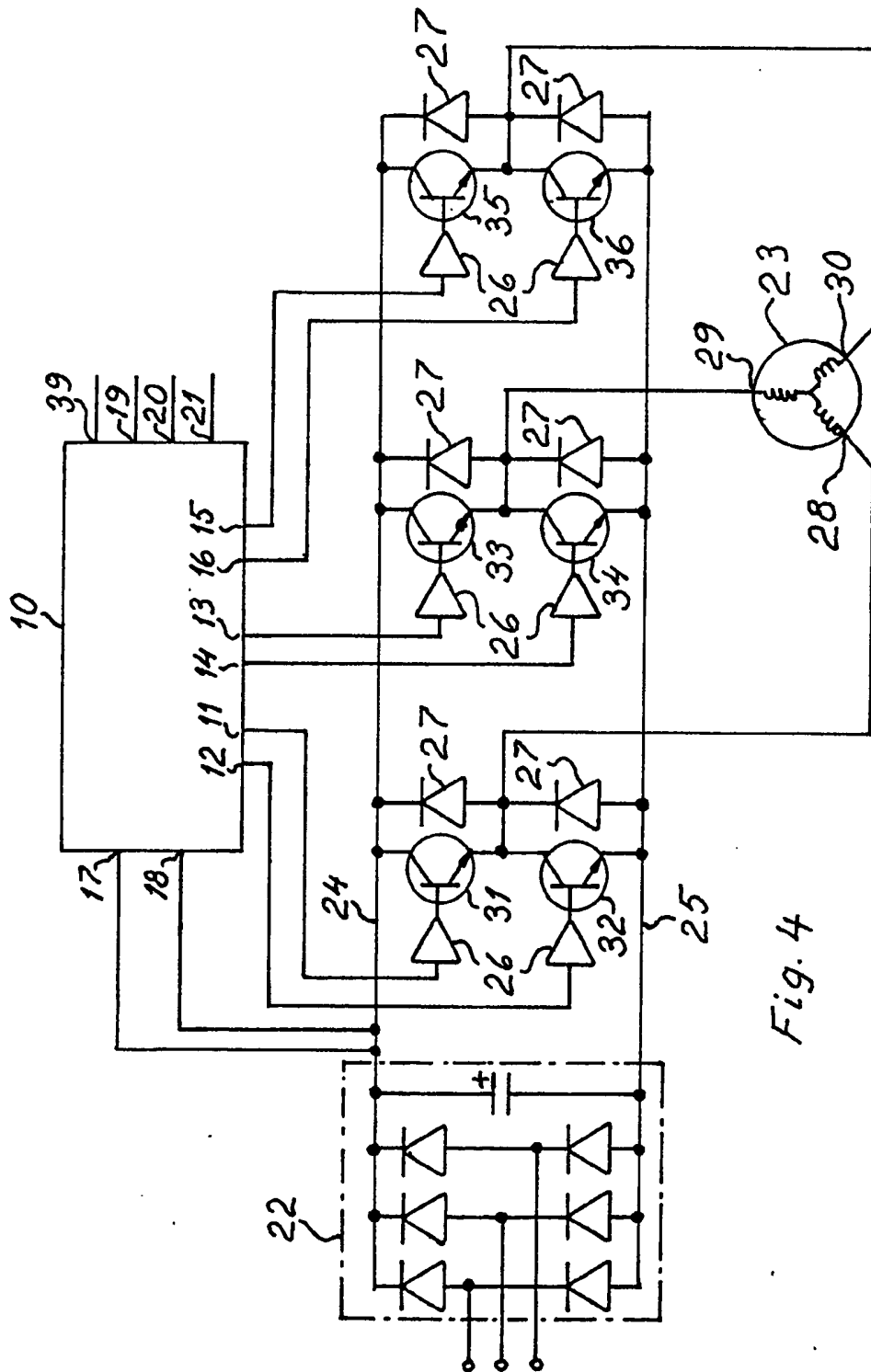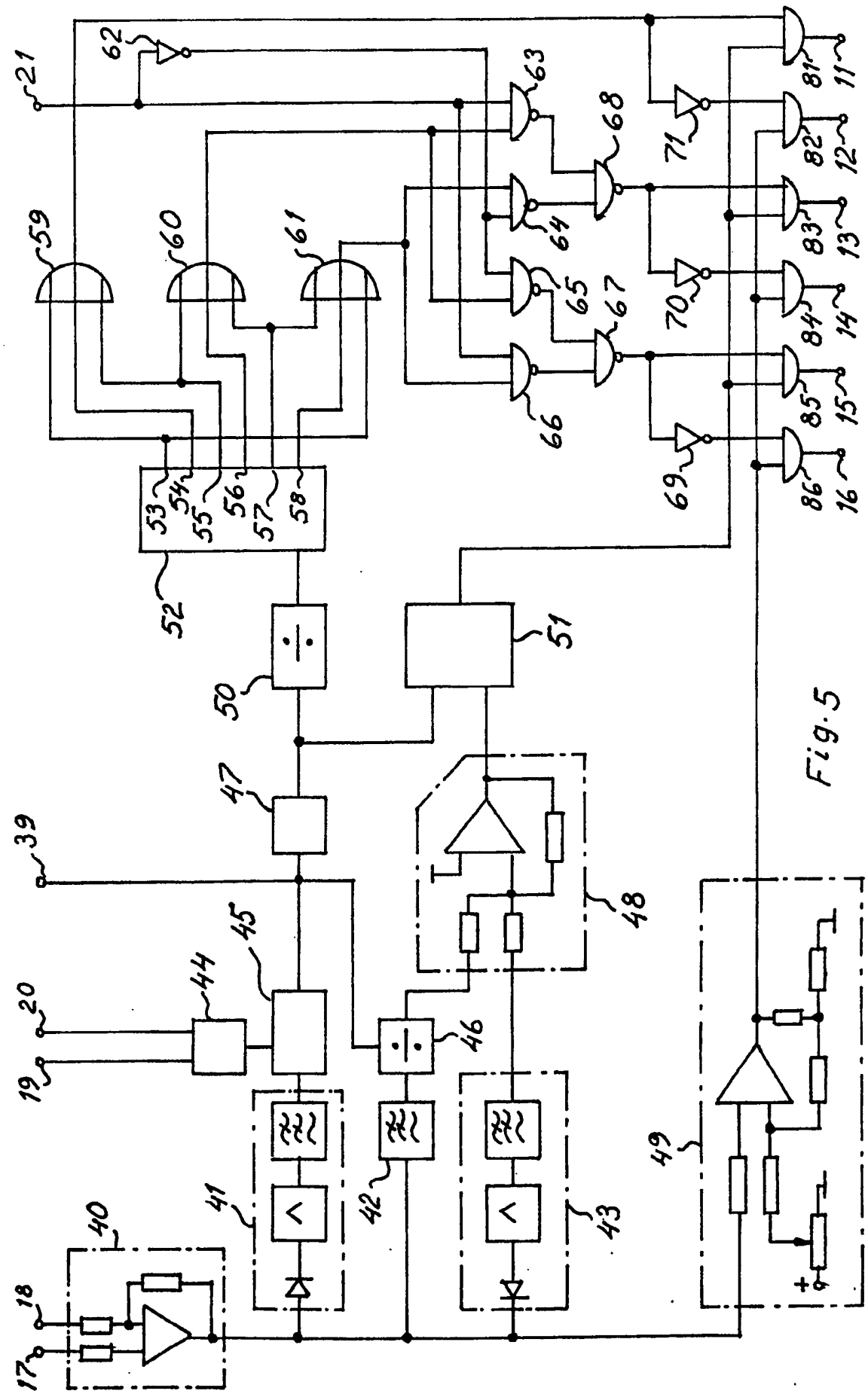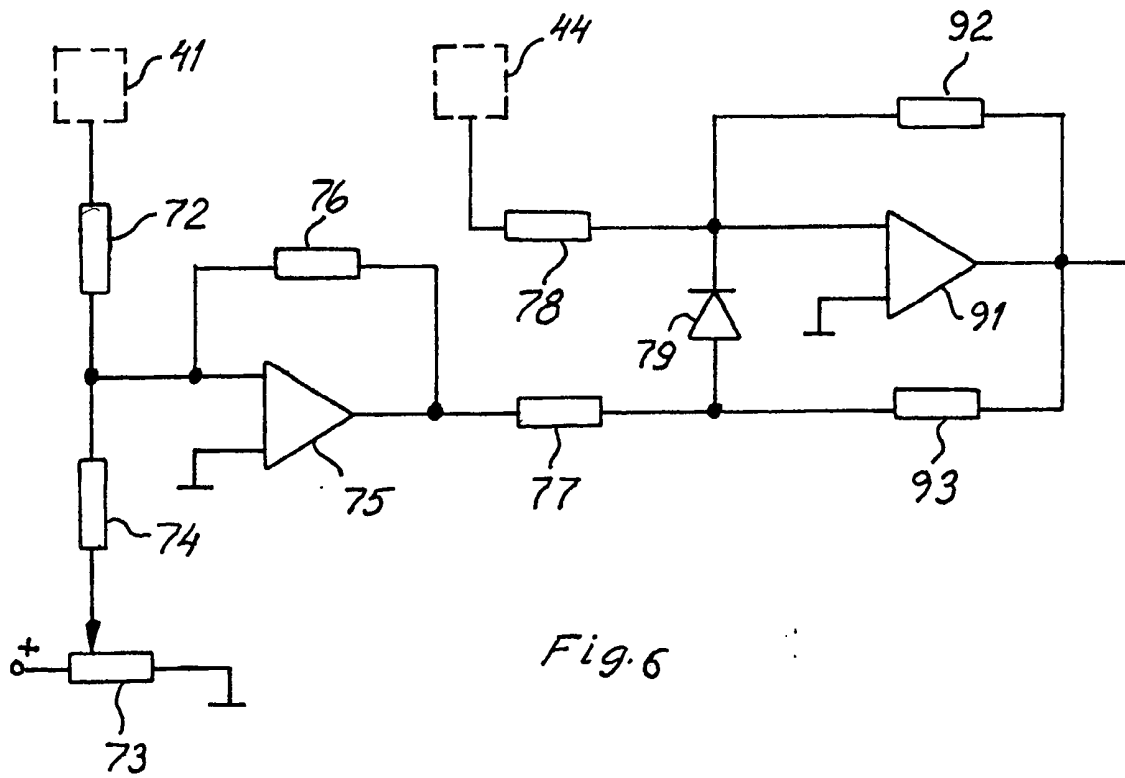3 ~/=/~ 4

Fig.2

Fig.3

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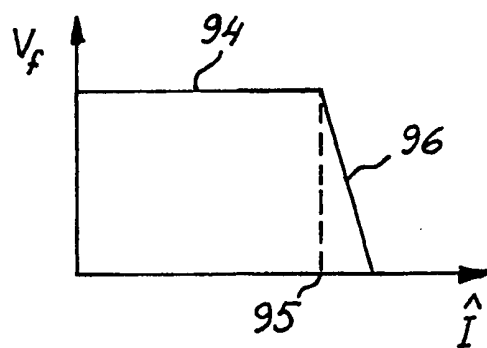

Fig. 4

Fig. 5

Fig. 6

Fig. 7

SPECIFICATION

Method and means for feeding electrical energy to a portable power tool

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The present invention relates to a method and a means for feeding electrical energy to a portable power tool.

In particular, the invention concerns a method and
10 a means for feeding energy to a portable power tool using a brushless electric motor.

Previously there have been available two different principal types of electric tools as far as the electrically powered prime mover is concerned. One of
15 these comprises a brush fed motor for connection to a conventional alternating current mains voltage of 50 or 60 Hz frequency. The other type comprises a brushless motor for connection to a non-variable voltage source of 150-4000Hz non-variable fre-
20 quency.

The first mentioned type of tool including a brush fed mains connected motor is disadvantageous in that the brushes produce sparks which may be hazardous in inflammable or explosive atmosphere,
25 and in that the brushes and commutator are exposed to a hard wear, especially when the tool is used in a dusty and/or corrosive atmosphere.

Concerning their operational features, brush motor tools have by their nature a high idling speed
30 and a very weak power-speed characteristic. Lately however, tools of this type have been equipped with electronic control means via which the idling speed is reduced to a suitable level. At the same time a stronger motor has been employed such that an
35 increased output power is obtained up to the new idling speed level. This means that the power-speed characteristic is improved and that the motor speed is better maintained at increased motor loads. Nevertheless, the power-speed relationship is still
40 not stiff enough to satisfy heavy duty demands. In, for instance, portable grinding machine applications a loss-of speed at increasing load on the grinding tool causes rapidly increasing wear of the latter.

Brush fed motor tools are also disadvantageous in
45 that they have a low output power-weight relationship. This means that for a given power size the weight of the tool is rather high, which of course is a serious drawback for a portable tool.

Brushless high frequency motor tools have a
50 stiffer power-speed characteristic than the brush fed motor type tool, which means that the brushless tool is better at maintaining speed at increasing motor loads. The stiffer the power-speed relationship is, the better from the viewpoint of tool wear as well as
55 production rate.

Previously available brushless motor tools, however, are disadvantageous in that their power feed means provide electrical energy of constant voltage and frequency. This means that due to the
60 lack of correlation between motor load and voltage amplitude over large parts of the speed range, the energy losses are high and overheating of the motor is a serious performance limiting factor for this type of tool.
65 Previous brushless motor tools are also disadvan-

tageous in that their use is limited to such areas where a non-portable high-frequency power supply is available. The type of power supply previously used in connection with portable tools is of the
70 rotary converter type.

Such converters are not only limited to specific and predetermined voltages and frequencies but have by their nature a high weight-to-power ratio and can not normally be made portable. For that
75 reason, prior art power supply means of this type are usually arranged to serve a number of tools through a local network, confined for instance within the premises of a factory.

It is an object of the present invention to avoid or
80 minimize one or more of the above disadvantages.

The present invention provides a method of energizing a manually supported power tool which includes a brushless electric motor, comprising the steps of feeding the motor with an alternating
85 current voltage, sensing continuously the magnitudes of the motor speed and the work load to which the motor is subjected, and adjusting continuously the amplitude and frequency of said alternating current voltage in response to the instantaneous
90 operating conditions of the motor as sensed.

In a further aspect this invention provides an electrical power feed means for supplying electrical energy to a manually supported power tool which includes a brushless motor, wherein are provided a
95 variable output voltage inverter, means for sensing the instantaneous load and speed of the motor, and control means for adjusting instantaneously the output voltage parameters of said inverter in a predetermined relationship to the sensed load mag-
100 nitude.

In accordance with the present invention the parameters of the supplied electric energy are automatically adapted to the instantaneous operating conditions of the tool motor in relation to
105 predetermined performance specifications. By this means there can be achieved an improved power-weight relationship as well as a stiffer power-speed relationship in electrically powered tools.

Further preferred features and advantages of the
110 invention will appear from the following detailed description given by way of example of a preferred embodiment illustrated with reference to the accompanying drawings in which:

Figure 1 shows a portable grinding machine
115 connected to an electric power supply via an inverter type feed means;

Figure 2 shows diagrammatically the torque/ speed characteristic of some prior art power tool drives in comparison with the characteristic
120 obtained using the present invention;

Figure 3 shows a graph illustrating the operating characteristic of a motor fed with power in accordance with the present invention;

Figure 4 shows the power supply unit;
125 *Figure 5* shows the controller of the unit shown in Figure 4;

. *Figure 6* shows a regulator of the controller of Figure 5; and

Figure 7 illustrates a transfer function for the
130 regulator of Figure 6.

Figure 1 shows a portable rotary grinding machine 1 fed 2 with electrical power from a supply unit 3 including a solid stage type inverter. In the latter an AC voltage of 50 or 60 Hz frequency is transformed
5 into an AC voltage of variable amplitude and frequency. As described in further detail below, the supply unit 3 comprises means for sensing the actual operating conditions of the motor of the machine 1 and automatically adapting voltage para-
10 meters, such as amplitude and frequency, in a particular way to these conditions.

In the chart shown in Figure 2, there are illustrated the torque/speed (M/n) characteristics of three different prior art electric rotary tools and a tool powered
15 in accordance with the invention. In this chart a comparison is made between four different rotary tools all marked with the same maximum speed. This maximum speed x, is the speed achieved under idle running of the tool.

20 The dashed line curve A illustrates the torque/ speed relationship of a tool having a brush fed series-wound motor. This type of motor is, as previously mentioned, characterized by its low torque idling speed features. For safety reasons,
25 however, the motor is dimensioned so as to avoid ever reaching the maximum speed level with which the tool is marked.

Together, the marked maximum speed over-estimation and the very weak torque/speed charac-
30 teristic results in this type of tool working at a normal load speed which is 30 to 40 per cent below the stated maximum speed level. This causes an undesirably high wear of the grinding wheel which is intended to be operated at or close to the marked
35 maximum speed level X.

The chain line curve B illustrates the operational characteristics of a rotary tool of the same type as the one discussed above except for the inclusion of an electronic control means by which the weakest
40 part of the torque/speed curve is "cut off". This tool is also marked with the maximum speed level X, because under a break down of the built in control means the motor speed would reach that level. So, for safety reasons, this tool always operates with an
45 undersized grinding wheel which in turn means too low a peripheral velocity and cutting speed.

The result is that this electronically controlled brush fed tool also has a normal working speed level some 30 to 40 per cent below the stated maximum
50 speed level. The only difference vis-a-vis the curve A tool is that this second tool (curve B) provides a higher torque at the working point speed level or a somewhat higher speed at a given output torque. Grinding wheel wear remains, though, at the same
55 high level.

The dotted line curve C illustrates the torque/ speed relationship of a high frequency brushless motor type prior art tool also discussed hereinbefore. The motor of this tool can never run faster than
60 what is determined by the frequency of the supplied voltage, and, therefor, no safety margin is needed in relation to the marked maximum speed level X.

Compared to the brush fed motor tools illustrated by the curves A and B, this tool provides a stiffer
65 torque/speed relationship at or just below the max-

imum speed level. However, due to the fact that this tool is fed with a non-variable frequency voltage, the torque drops drastically as the motor speed is decreased below a maximum torque level. This
70 means that the tool is very easily stalled and overheating occurs.

Looking now at the continuous line curve D representing the torque/speed relationship of a tool of the present invention, there are four significant
75 characteristics to be noted.

1). No safety margin vis-a-vis the maximum speed level X is required since the motor speed is determined by the frequency of the supplied voltage.

2). The torque/speed relationship is very stiff at
80 or adjacent the idling speed level, which means that the tool has a working point very close to the maximum speed level. The benefit of this is a high cutting speed and a low grinding wheel consumption.

85 3). The torque remains unaffected at decreasing motor speed resulting in a very small risk of stalling and overheating of the motor.

4). The output torque is considerably higher than for the various prior art tools - especially the brush
90 fed motor tools.

A fifth point to be noted in connection with the operating characteristics of the tool of the present invention is that the weight and size of the tool in spite of its higher performance level need not exceed
95 the weight and size of any of the other tools.

Figure 3 illustrates how the output torque M of the tool motor is kept up at decreasing motor speed n as mentioned in paragraph No. 3 above. When the load applied on the tool reaches a certain level the speed
100 starts falling. By successively lowering and adapting the frequency to the motor speed, as illustrated by the curves f_1, f_2 and f_3, the output torque of the motor is maintained at its top level down the speed range. Simultaneously, energy losses are considerably re-
105 duced and so is the risk of overheating of the tool.

The following discussion of the aims and advantages of a tool powered in accordance with the invention will further explain and clarify the inventive step by which the method and power feed
110 means of the present invention differ from the prior art designs.

In accordance with the present invention, the above discussed prior problems are solved by feeding electrical energy to a power tool including a
115 brushless motor via an individual inverter means the output voltage parameters of which are automatically adjusted in a predetermined relationship to the instantaneous operating conditions of the motor.

By utilizing the power feed means including an
120 electronic inverter with variable output voltage it is made possible to automatically adjust the voltage amplitude in all the different operating conditions of the motor in such a manner that the highest possible output is delivered at peak load conditions and that
125 the smallest possible energy losses are achieved over the main part of the speed range. Small energy losses are of vital interest just because they reduce the risk of overheating of the motor.

Furthermore, the new concept of the present
130 invention also provides for an automatic adaptation

of the voltage frequency to the actual motor speed. This makes it possible not only to avoid undesirable current peaks during starting sequences but to maintain the maximum output torque M of the
5 motor at decreasing motor speed n.

Power feed means comprising solid-state electronic inverters for brushless motors are previously known per se, see for instance "Solid-Stage Control of Electric Drives" by R. G. Schieman, E.A. Wilkes and
10 H. E. Jordan, published in Proceedings of the IEEE, Vol. 62, No. 12, December 1974. Inverter type power feed means, however, have not previously been used in connection with portable power tools which in fact is a very special technical field from the
15 viewpoint of load characteristic and performance requirements. Instead, inverter type power feed means for brushless motors have been described either generally or in static machine applications where the requirements are to obtain a free choice of
20 motor speed levels by changing the frequency and/or to bring down expensive energy losses under various motor load conditions, for instance during starting-up sequences.

Such known applications are totally different from
25 the portable tool application contemplated by the present invention. In the latter case, the primary object of utilizing an inverter feed means is *not* to accomplish more than one speed level and *not* to bring down high energy costs as in large static
30 machinery.

Instead, the possibility to change rapidly the output voltage amplitude provided by the inverter feed means is now utilized to squeeze out the maximum power capacity of a motor of a given size.
35 Due to the fact that the output power of the motor is square related to the voltage amplitude a drastic increase in the motor output power is obtained by raising the voltage amplitude by several times as the motor load is increased from idling level to peak
40 level.

This is in fact a new and efficient means for obtaining a very stiff power-speed relationship from an electrical motor. In, for example, portable grinding tools in which there is a very frequent motor load
45 variation between the zero and maximum levels a rapid change in the voltage amplitude results in a tool characteristic of a high power-weight ratio as well as a very stiff power-speed relationship.

The variable frequency feature of the electronic
50 inverter type of power feed means also provides the advantage of maintaining motor torque at peak level when too heavy a load makes the motor speed drop. This is an essential feature in the portable tool application only, because none of the other types of
55 machinery previously mentioned in connection with inverter type power feed means has a performance specification wherein the motor is frequently overloaded and sometimes stalled under normal operation. A fully maintained output torque at decreasing
60 motor speed, though, is an important feature since it prevents a lot of unnecessary stalling interruptions to the tool's operation.

Utilizing the electronic inverter type power feed means for portable power tools also means that the
65 power tools do not necessarily have to be limited in

their use to the limits of a local power distribution network. Recent development in semiconductors makes it possible to bring down the size and weight of the electronic inverter type power feed means,
70 which means that the latter may be made portable together with the tool either as a separate or even a built-in unit. This means in turn that the field of use of brushless high-frequency power tools may be greatly widened from very restricted areas covered
75 by local power networks to all places where the public 50 or 60 Hz voltage network is available.

The power supply unit 3 which is schematically illustrated in Figures 1 and 4 comprises a three-phase rectifier 22 which is connected 4 to a standard
80 fixed frequency mains supply. The rectifier 22 delivers direct current of substantially constant voltage to conduits 24, 25, which constitute a positive 24 and a negative 25 terminal of a direct current supply for an inverter. The inverter comprises six switching ele-
85 ments 31-36 for successively connecting motor terminals 28, 29, 30 on a brushless alternating current motor 23 to the positive terminal 24 and the negative terminal 25 of the direct current supply. The switching elements are in the drawing shown as
90 transistors but could, of course, be combinations of thyristors or other elements. A diode 27 is placed in anti-parallel over each transistor to take care of reactive currents at the switching off of the transistor. To control the inverter, control signals are
95 supplied from outputs 11-16 on a controller 10 as shown in Figure 5. These control signals are supplied via amplifiers 26 to the base of respective transistor. Controller 10 is provided with inputs 17, 18 through which the direct current in conduit 24 is
100 sensed. Controller 10 is further provided with an output 39 and inputs 19, 20, 21. Output 39 is only used if, during operation, it is desired to change the direction of rotation of the motor. The direction of rotation is selected by applying a logical signal to
105 input 21. If rotation in only one direction is desired input 21 is connected either to a positive voltage or common. The speed of motor 23 may be changed by variation of a voltage applied to input 19. If, as for instance in a grinding machine, it is desired to drive
110 the motor at a certain speed, input 19 is connected to a suitable voltage corresponding to the desired speed. Input 20 is intended for receiving a start/stop signal by which rotation or no rotation is chosen.

Controller 10, which is shown in more detail in
115 Figure 5 comprises a sensing means 40 for sensing the direct current in conduit 24. This current is presented as a voltage between inputs 17 and 18. The output signal of sensing means 40 is applied to a first peak detector 41, a low-pass filter 42, a second
120 peak detector 43 and a comparator 49. Peak detectors 41 and 43 comprise diodes to react on positive and negative signals respectively. The peak detectors also comprise low-pass filters. First peak detector 41 preferably has a time constant of about 4/f
125 where f is the maximum fundamental frequency of the current supplied to motor 23. The cut-off frequency, -3dB, of peak detector 41 is preferably about 0.1 f. Low-pass filter 42 preferably has about the same cut-off frequency. Second peak detector 43
130 preferably has a time constant of about 1/f and a

cut-off frequency of about 0.5 f.

The peak value signal from peak detector 41 is supplied to a first regulator 45, which is shown in more detail in Figure 6. Input signals from inputs 19 and 20 are supplied to a means 44 in form of a ramp generator. Ramp generator 44 comprises one or two operational amplifiers connected as integrators to supply regulator 45 with an increasing ramp voltage at motor start acceleration and a decreasing ramp voltage at motor stop deceleration. In this way it is possible to avoid that the normal speed maximum load current is exceeded when the motor is started or stopped. A change in the speed demand signal at input 19 is also integrated by ramp generator 44. Thus it takes some time before the output of ramp generator 44 becomes fully adapted to the input signals.

The peak value signal from first peak detector 41 is applied to one of the inputs of operational amplifier 75 via resistor 72. This signal is compared with a reference signal preset on variable resistor 73 and fed to the amplifier via resistor 74. The amplifier is provided with a feed-back resistor 76. The output signal of amplifier 75 is via a resistor 77 applied to diode 79. The output signal from ramp generator 44 is via resistor 78 supplied to one of the inputs of operational amplifier 91. Amplifier 91 is provided with a first feed-back resistor 92 and a second feed-back resistor 93 in series with diode 79. Resistor 93 has a much lower resistance than resistor 92. Preferably the ratio is about 1/20. If the output signal from amplifier 75, measured at diode 79, is more negative than the output signal from amplifier 91, measured at diode 79, is positive, diode 79 is reverse-b iased. The closed loop amplification of amplifier 91 is then high. Regulator 45 then operates according to line 94 in Figure 7 assuming constant signal from ramp generator 44. If the signal from first peak detector 41 decreases, the output signal from amplifier 75 becomes less negative and at a certain signal level, level 95 in Figure 7, which is preset on resistor 73, diode 79 becomes forward-biased. The closed loop amplification of amplifier 91 is now drastically reduced so that first regulator 45 delivers a frequency controlling signal according to line 96 in Figure 7. This signal becomes zero at about 120% of the signal at level 95. The frequency controlling signal from the output of amplifier 91 is delivered to a voltage-controlled oscillator 47, output 39 and an analog divider 46, e.g. Analog Devices AD 534. The voltage-controlled oscillator produces an output signal whose frequency is proportional to the input voltage.

The rectified mean value signal obtained from low-pass filter 42 corresponds to the power supplied to motor 23 because the voltage of the direct current supply 24, 25 is substantially constant. This signal is supplied to divider 46 where it is divided with the frequency controlling signal, which is the demand signal for rotational speed of motor 23. The output signal of divider 46 will thus correspond to the torque demand from motor 23. This output signal, first voltage controlling signal, is supplied to a second regulator 48. The negative peak value signal, second voltage controlling signal, obtained from

second peak detector 43 is also supplied to regulator 48 so that the output signal of regulator 48 becomes proportional to the difference between the first and the second voltage controlling signals. The negative peak value signal from peak detector 43 corresponds to the degree of magnetization of motor 23. This signal is obtained from negative pulses which are fed back to the direct current source when the transistors 31-36 are switched off. By controlling the level of these negative pulses it is possible to obtain a predetermined level of magnetization of the motor allowing both a high power to weight ratio and the avoiding of oversaturation, which would give un-acceptable losses.

If the signal from sensing means 40 exceeds a predetermined level the output of comparator 49 becomes low. As a result outputs 12, 14 and 16 and AND gates 82, 84 and 86 respectively will be low. This means that the lower transistors 32, 34 and 36 of the inverter will be turned off so that the motor terminals 28, 29 and 30 will be cut off from the negative terminal 25 of the direct current supply. This cutting off thus functions as transient current protection for the inverter.

The output signal from voltage-controlled oscilla-tor 47 is supplied to a timer 51, preferably an industrial timer of standard type 555, and to a divider 50. Divider 50 is preferably a programmable counter which delivers a pulse train having a frequency which is equal to the frequency of the input signal divided by a chosen constant. Timer 51 delivers a pulse train whose frequency is equal to the frequen-cy of the output signal from voltage-controlled oscillator 47. The pulse width is controlled by the output signal from second regulator 48. This pulse train is supplied to AND gates 81, 83 and 85. The pulse train from divider 50 is supplied as clock signal to ring counter 52. In the ring counter a 1 and five O's are stored. The 1 is shifted around by the pulse train from output 53 through 58 and back to 53. This makes one period of the fundamental frequency of the current supplied to motor 23. Outputs 53-58 of ring counter 52 are decoded by OR gates 59, 60 and 61. The output of each of these gates is high half the time and low half the time. A logic signal inverter 62 and NAND gates 63-68 are provided for selecting direction of rotation of motor 23. The output signals of gates 59, 60 and 61 are supplied to AND gates 81-86 for controlling the actuation of switching transistors 31-36 in the inverter. The inputs of gates 82, 84 and 86 are provided with logic signal inverters 71, 70 and 69 respectively.

Because the pulse width of the pulses leaving timer 51 remains constant independent of frequency if the signal from regulator 48 is constant, the mean value over half a period of the fundamental frequen-cy of the voltage applied to any of the motor terminals will change simultaneously with the fre-quency as required by basic electromagnetic laws. Additional control of the mean value voltage is obtained by variation of the pulse width, which is controlled by regulator 48.

As previously mentioned, the risk of overheating a tool of the present invention is considerably reduced as a result of the frequency adjustment. Neverthe-

less, there is still a risk that the temperature of the motor could rise to an unacceptable level during frequent overloading of the tool. In order to prevent the motor from burning out, one or more heat
5 sensors may be attached to the motor windings and arranged to produce a signal in response to attainment of a predetermined temperature level. This signal is preferably used to directly cause a power supply interruption and/or an optical signal to inform
10 of overheating.

CLAIMS

1. A method of energizing a manually supported
15 power tool which includes a brushless electric motor, comprising the steps of feeding the motor with an alternating current voltage, sensing continuously the magnitudes of the motor speed and the work load to which the motor is subjected, and
20 adjusting continuously the amplitude and frequency of said alternating current voltage in response to the instantaneous operating conditions of the motor as sensed.

2. A method according to claim 1, wherein the
25 tool is energized via an inverter means, and the amplitude of the average rectified voltage of said inverter means is increased at least twice as the motor load increases from an idling condition to maximum.
30 3. A method according to claim 1 or claim 2, wherein the amplitude of the average rectified voltage of said inverter means is increased to at least twenty percent above its normal value for continuous maximum motor power output as the max-
35 imum motor load is reached.

4. A method according to any one of claim 1 to 3, wherein under peak load motor conditions the voltage frequency is automatically adapted to the decreasing motor speed to maintain maximum
40 output torque of the motor.

5. An electrical power feed means for supplying electrical energy to a manually supported power tool which includes a brushless motor, wherein are provided a variable output voltage inverter, means
45 for sensing the instantaneous load and speed of the motor, and control means for adjusting instantaneously the output voltage parameters of said inverter in a predetermined relationship to the sensed load magnitude.
50 6. A power feed means according to claim 5, wherein said means for sensing the load on the motor comprises current responsive signal producing means connected to the direct current supply of the power feed means.
55 7. A power feed means according to claim 6, wherein said increase in voltage amplitude is obtained by a pulse width modulator connected at its input end to a regulator connected to said current responsive signal producing means and at its output
60 end to the inverter switches of the voltage inverter.

8. Electric power feed means according to any one of claims 5 to 7, wherein said inverter is formed and arranged to form, together with the tool, a single self-contained unit.
65 9. A method for electrically energizing

ly supported power tool according to claim 1 substantially as described hereinbefore with particular reference to the accompanying drawings.

10. An electrical power feed means for supplying
70 electrical energy to a manually supported power tool according to claim 5, substantially as described hereinbefore with particular reference to the accompanying drawings.